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ACQUISITION AND REDUCTION OF BLADE-MOUNTED PRESSURE TRANSDUCER DATA FROM A LOW ASPECT RATIO FAN

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This report details the acquisition and reduction of blade-mounted, high-response, pressure transducer data. These data were acquired during the Augmented Damping of Low Aspect Ratio Fans (ADLARF) test conducted at the Compressor Research Facility (CRF) located at Wright-Patterson A.F.B. , Ohio. This report, which is exclusively concerned with the acquisition and digitizing of the blade-mounted data, is intended to compliment other related reports by documenting the data acquisition and reduction procedures.

The primary goal of this work is to detail the methodology by which unsteady blade forces and momentum can be determined using blade-mounted pressure transducer data. The secondary goal is to use these data to show how inlet distortion and resulting unsteady forces affect the blade resonance of high-speed fans. By achieving the primary goal in this report, it is hoped that the secondary goal can be better achieved using data from future tests.

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1.0 INTRODUCTION

This report details the acquisition and reduction of blade-mounted, high-response, pressure transducer data. These data were acquired during the Augmented Damping of Low Aspect Ratio Fans (ADLARF) test conducted at the Compressor Research Facility (CRF) located at Wright-Patterson A.F.B., Ohio. This report, which is exclusively concerned with the acquisition and digitizing of the blade-mounted data, is intended to compliment other related reports by documenting the data acquisition and reduction procedures.

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1.1 ADLARF Article

The test article is a high-speed, two stage, low aspect ratio fan. Table 1.1 shows the baseline performance of this machine at design speed. The first stage rotor is a single piece, 16 blade blisk designed to operate at rotational speeds in excess of 13,000 rpm. Technically, the higher pressure ratio of this test article classifies it as a compressor rather than a fan. The terms "fan" and "compressor" will be used interchangeably throughout this report.

1.2 ADLARF Distortion Hardware

The distortion part of the ADLARF test program determined how various types of inlet flow distortion affected the performance and operation of the compressor. The forced-response behavior of the first-stage rotor had been documented during previous tests with and without distortion, but blade mounted pressure transducer data were not available from these tests. Using the foreknowledge of where and under what

Table 1.1 Fan Performance at Design

Parameter	Value
Corrected Speed, Percent	98.6
Efficiency, Percent	85.2
Corrected Speed	13,022 rpm
Corrected Tip Speed	485.2 m/sec
Corrected Mass Flow	71.8 kg/sec
Total Pressure Ratio	4.30

conditions the first stage rotor would resonate, blade-mounted, high-response pressure transducer data were acquired at or near resonance at various operating points.

Inlet flow distortion patterns were imposed on the machine with variable mesh distortion screens positioned upstream of the first stage rotor as shown schematically in Figure 1.1. The blade-mounted pressure transducer data used in this report were acquired with three different distortion screens installed. These screens imposed a 1st harmonic (2/rev), 2nd harmonic (3/rev), and 7th harmonic (8/rev) forcing function on the compressor, respectively. Schematics of these screens are shown in Figure 1.2. In this figure, darker shades indicate higher mesh density and therefore more blockage.

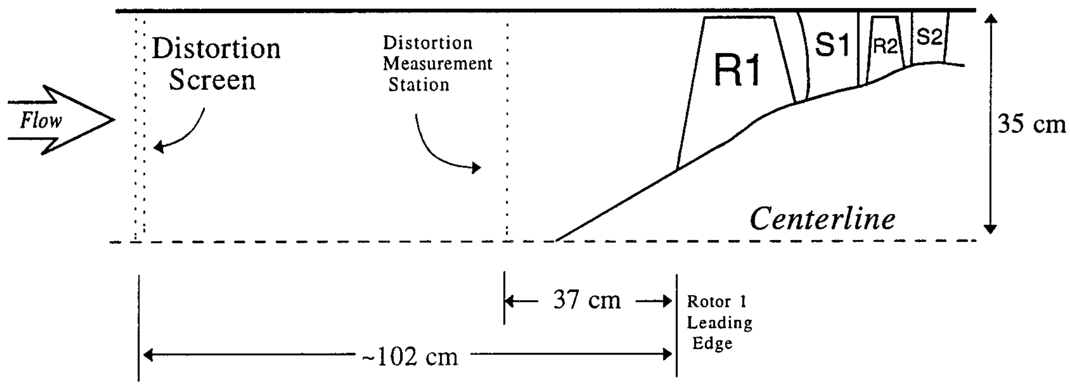

Figure 1.1 Profile Schematic of ADLARF Compressor

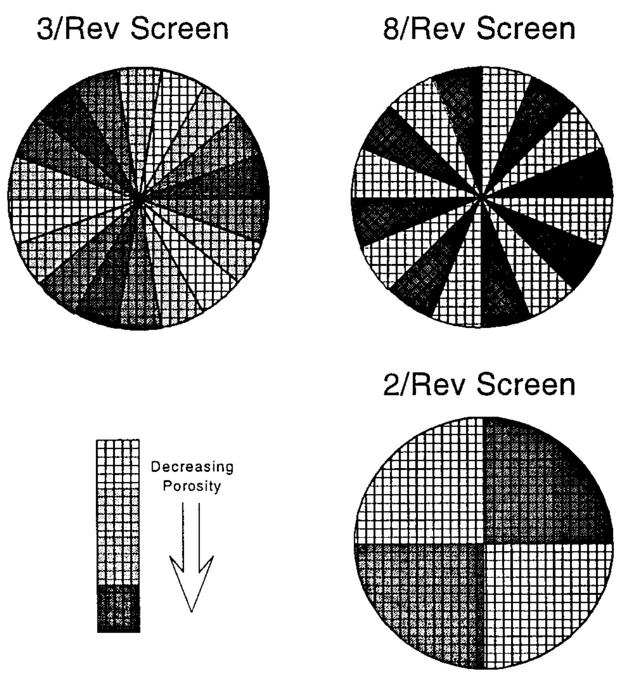

Figure 1.2 Distortion Screen Patterns

2.0 DATA ACQUISITION

The data for this study were obtained using 14 modified pressure transducers that were physically attached to two adjacent fan blades (blades #16 & #1) on the first stage rotor as shown in the photograph in Figure 2.1. The transducers were installed along a line representing the 85% stream line used in the initial design of the rotor. This resulted in the transducers being at an angle to the rotor centerline as shown in Figure 2.2. Two sets of seven transducers were installed on each of two blades, the first set on the pressure side of one blade and the second set on the suction side of the other. A sketch in Figure 2.3 shows how the transducers were mounted in the blades. The measurement side of each transducer was open to one side of the blade while the reference side (the vent hole in the figure) was open to the other. In this way, only the differential pressures across the blades were measured.

Specific information concerning the transducers and associated signal processing is given in Table 2.1. The transducers had a 345 kPa (50 psid) range, which was more than adequate to withstand the expected pressure variations across the blade. The gain was sufficient to provide a maximum 5 V zero-to-peak signal, full range, to the analog tape player used to record the transducer signals for post-test processing. The highest possible frequency of interest was estimated to be approximately 30 kHz; (16 blades) x (8 per rev) x (240 Hz max. rotor speed) = 30,720 Hz. Tape speed settings of 60, 120, and 240 inches per second were available allowing distortion-free recording of signals of up to 40, 80, and 120 kHz respectively. A conservative decision to record at 120 inches per second was made, which allowed frequencies much higher than expected to be recorded.

Using this acquisition system, data at a variety of compressor operating conditions were obtained. Three different inlet distortion screens were used for the forced response study: 2/rev, 3/rev, and 8/rev (Figure 1.2). Data were acquired with each of these screens installed at operating speeds near the resonant speeds of the rotor. Due to the hostile operating environment to which the transducers and the associated wiring were exposed, the transducers had a rather short life expectancy,

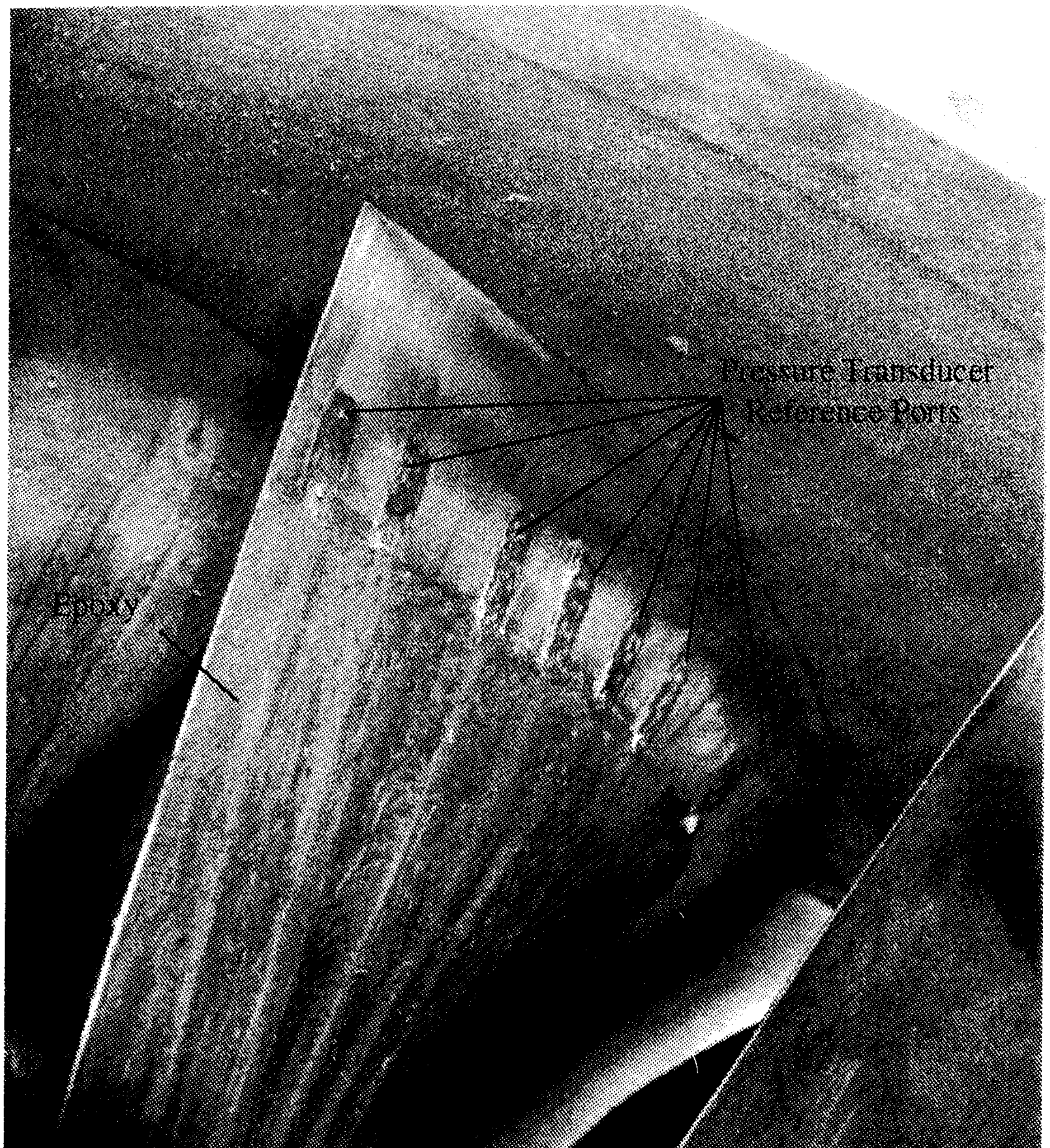

Figure 2.1 ADLARF Blade-Mounted Pressure Transducers

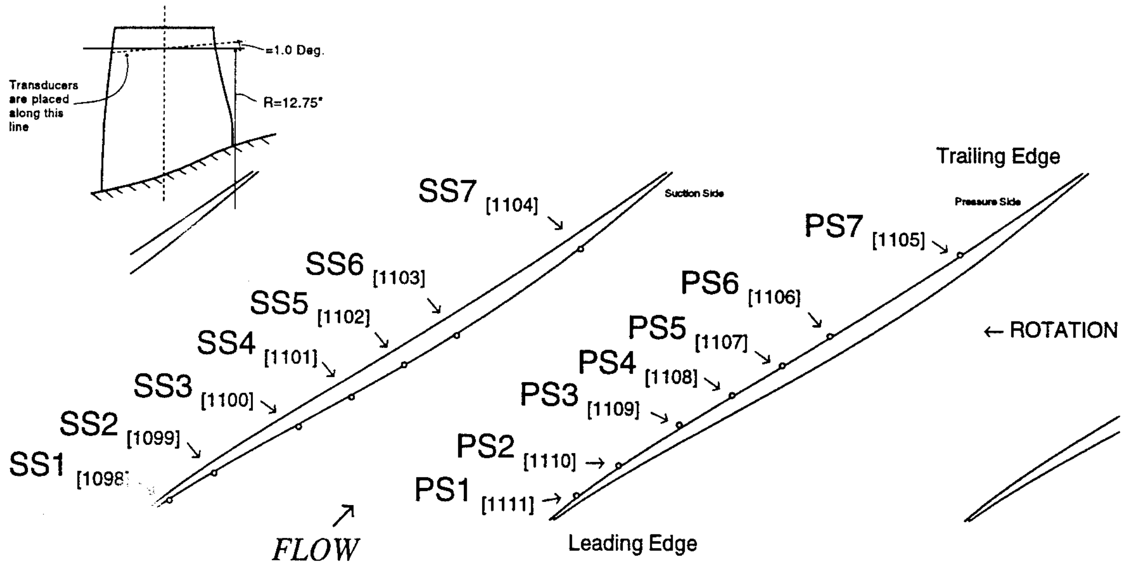

Figure 2.2 Blade-Mounted Transducer Positions

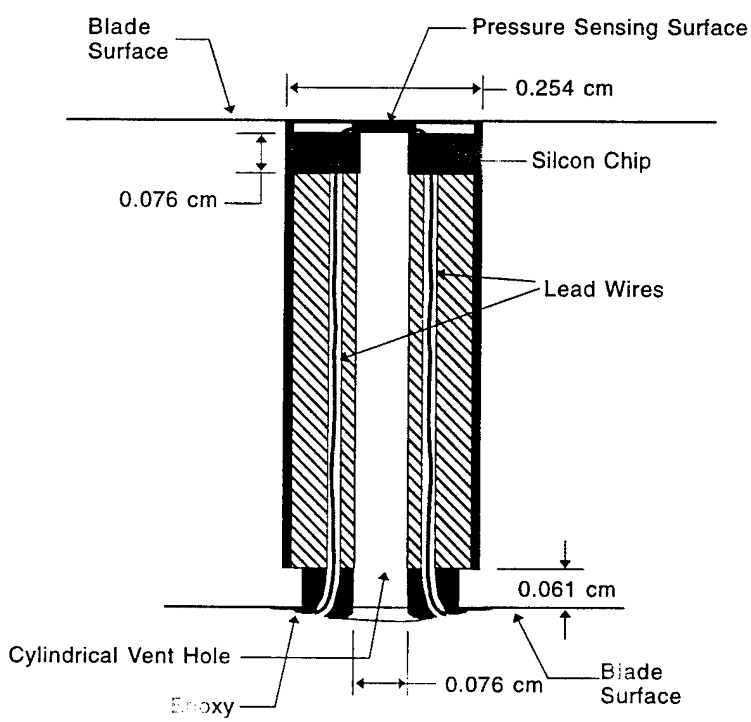

Figure 2.3 Pressure Transducer Mounting Scheme

Table 2.1 Transducer and Recording Information

Blade-Mounted Static Pressure Transducer	
Model	Kulite XCQ-093
Differential Pressure Range	235 kPa (50 psid)
Operational Temperature Range	-18°C to 180°C (0°F to 350°F)
Compensated Temperature Range	24°C to 150°C (75°F to 300°F)
Sensitivity	~0.44mV/kPa (~3mV/psi)
Temperature Sensitivity	$<$0.5% full scale at 93°C (200°F)
Centrifugal Sensitivity	$<$1% full scale at 50,000 g's
Excitation	5 V
Gain	500
Low Pass Filter	40 kHz
Coupling	AC

especially at high speeds. For this reason, only data for a limited number of operating conditions were available. For the purposes of this report, five operating conditions were chosen for study. These conditions and the operational transducers in each case are detailed in Table 2.2. All five data points were acquired at peak efficiency for each rotor speed. Note that in none of the five cases were all 14 transducers functioning at the same time. Data acquired at several other operating points were available but are not included in this report. For a complete list of all acquired data, see Appendix A.

Table 2.2 Blade-Mounted Transducer Data Points

#	Distortion	RPM*	Mode**	Available Transducers
1	3/rev	8100	1F	P2,P3,P4,P5,P6,P7,S3,S4,S5,S6,S7
2	8/rev	9100	1T-2F	P2,P4,P5,P6,P7,S3,S4,S5,S6,S7
3		10370	1T-2F	P2,P4,P5,P6,P7,S3,S4,S5,S6,S7
4		13200	1-2S	P2,S3,S4,S5,S7
5	2/rev	14245	1F	P2,S3,S4,S5,S7

* This is the actual mechanical speed.
** F=bending or flex
T=torsional
S=strike

3.0 DATA REDUCTION

After the test, the analog recorded data were digitized for further analysis. Several factors went into determining the sample rate to use for the digitizing process. First, the size of the data sets had to be kept to a minimum so the files could be easily managed. Since this study was only intended to be a proof of concept, larger data sets were unnecessary. Second, the data resolution had to be sufficient to show the expected pressure fluctuations. Third, the sample rate had to be high enough so that the frequencies of interest would not be affected by signal aliasing. And finally, the number of rotor revolutions that occur over the time span of a given data set had to be great enough for the eventual data processing to be meaningful. With these factors in mind, the sample rate, the low-pass filter frequency setting, and the data set size for each of the five test conditions were determined.

Calculating the minimum required sample rate was accomplished by considering both the rotor frequency and the expected frequency of the pressure fluctuations at a given test condition. The frequency of the pressure fluctuations at any given rotor speed depended upon the distortion screen in use. For example, the 1st harmonic or 2/rev screen introduced a nearly sinusoidal pressure fluctuation with two cycles (or periods) per rotor revolution. The other two screens introduced similar variations with 3 and 8 cycles per rotor revolution, respectively. Therefore, the frequency of the static pressure fluctuations, or the *frequency of interest*, was equal the number of cycles, or screen periods, multiplied by the rotor frequency.

Normally, the minimum sample rate is determined by anti-aliasing considerations. To minimize the effects of signal aliasing, a sample rate 2 to 4 times greater than the highest expected frequency of interest is usually chosen. However, there were special data processing considerations in this case that required an even higher sample rate. The algorithms used to process these data required a higher number of samples per period for maximum accuracy [1]. A sample rate 7.3 times greater than the expected frequency of interest was thought to be ideal (Figure 3.1). By using this sample rate, aliasing is minimized because of the large number of

samples per cycle. Furthermore, the noninteger multiple reduced the chances that large amplitude harmonics associated with the frequency of interest would appear in the digitized data. With this in mind, the minimum sample rate was determined by the following relations;

$$f_{sample} = 7.3 N_{screen} f_{rotor}$$

where,

f_{sample} = Minimum sample rate or frequency,

N_{screen} = Number of screen periods,

f_{rotor} = Rotor frequency.

The actual sample rates used for each of the five test cases were round numbered values nearly equal to the calculated values.

All of the pressure transducer signals were processed through low-pass analog filters before digital conversion. The filter frequency settings were determined mostly on the basis of signal aliasing considerations. This required that frequency components greater than half the sample frequency be significantly reduced in amplitude. It was also important to consider the effect the filter had on the frequency of interest, since these analog filters slightly attenuate frequencies lower than the cut-off value (Figure 3.2). Generally, an amplitude attenuation of -20 dB is sufficient to reduce problems associated with signal aliasing. The filter frequency response diagram in Figure 3.2 shows that frequencies greater than approximately 125% of cut-off value, f_c , are sufficiently attenuated by the filter. Therefore, low-pass filter cut-off values no greater than 40% of sample rate were chosen. Lower values were used when possible. In all cases, the frequency of interest was no more than 90% of the low-pass cut-off frequency, which reduced attenuation of important frequencies. In most cases, the frequency of interest was less than 70% of the cut-off value, which

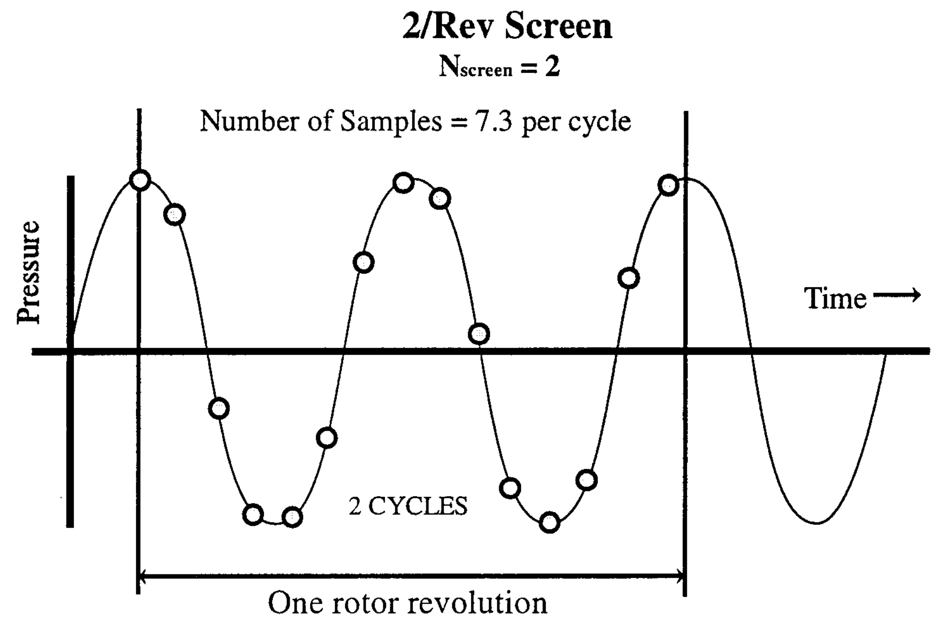

Figure 3.1 Representation of Expected Blade-Mounted Transducer Signal

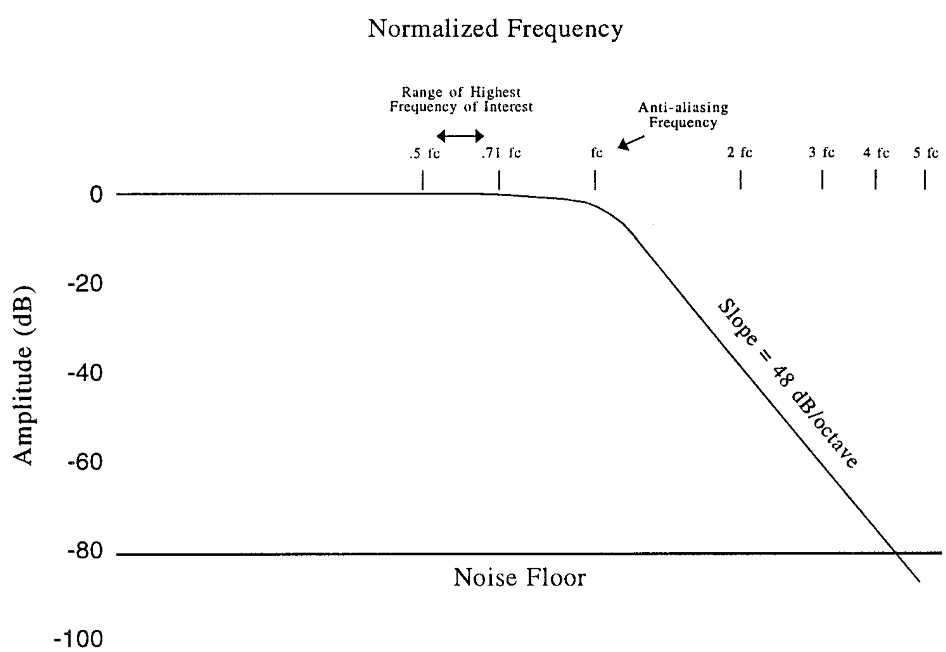

Figure 3.2 Low-pass Filter Frequency Response

eliminated attenuation of important frequencies altogether. Unfortunately, the limited number of filter settings below 2000 Hz made it difficult to avoid the slight attenuation of important components without using larger sample rates.

The length of the data sets were determined by data processing requirements and the manageability of the resulting computer data files. A minimum of 150 rotor revolutions per data set was determined to be sufficient for data processing purposes, but a consistent time length was thought to be useful as well. Therefore, most of the data sets included well over 150 rotor revolutions of data, since at least 1 second's worth of data were obtained in every case.

During the test, the compressor operating point was held steady at each of the test conditions for approximately 2 minutes. This was done to give the compressor time to stabilize at the new operating point before any steady-state data were acquired. In all five cases, analog data were digitized sometime during the last 30 seconds of the 2-minute recording window.

Table 3.1 shows some of the digitizing parameters and related information for each of the five test cases. The analog tapes (per CRF nomenclature) on which the data were recorded are listed, as well as the approximate time periods for the 2-minute steady-state operating points. The corrected and mechanical rotor speeds are also shown.

After digitization, each transducer signal was digitally high-pass filtered to remove DC offset. All frequencies less than 10 Hz were attenuated or removed in this fashion. Next, the voltage signals were converted to engineering units using bench calibration data. Correction of the data due to transducer temperature or centripetal acceleration was not believed to be necessary, since errors associated with either of these were determined to be small. The last step in the data reduction process was to write the data to computer files in Macintosh ASCII format. This final step was necessary since all the data processing was to occur on Machintosh computers. An example computer data file is presented in Appendix B.

Table 3.1 Digitizing Parameters

Condition	Analog Tape #	Low-Pass Analog Filter	Sample Rate	Data Set Size	Number of Revolutions
3/Rev, 8100 rpm (N_{cor}=8094 rpm)	AR 1656 18:05-18:07	800 Hz	3000 sps	2 sec (6000 samp.)	~270 revolutions
8/Rev, 9100 rpm (N_{cor}=9093 rpm)	AR 1656 21:19-21:21	2000 Hz	10000 sps	1 sec (10000 samp.)	~152 revolutions
8/Rev, 10370 rpm (N_{cor}=10364 rpm)	AR 1656 21:23-21:25	2000 Hz	10000 sps	1 sec (10000 samp.)	~173 revolutions
8/Rev, 13200 rpm (N_{cor}=13190 rpm)	AR 1700 18:14-18:16	2000 Hz	13000 sps	1 sec (13000 samp.)	~220 revolutions
2/Rev, 14245 rpm (N_{cor}=14245 rpm)	AR 1700 19:54-19:56	2000 Hz	5000 sps	1 sec (5000 samp.)	~236 revolutions

4.0 DATA VALIDITY AND ERROR

A rudimentary uncertainty analysis was conducted on the blade mounted pressure transducer system after the test. This analysis was based on the following assumptions:

1. The transducers were exposed to a 90°C (200°F) temperature variation.
2. The slipring noise and buffer amp noise was negligible.
3. The frequency response of the applied pressures was 40 kHz.

With these assumptions, a 3 kPa (0.44 psid) or 0.88% FS uncertainty was estimated for transducer measurements recorded on analog tape. The digitizing process brought the estimated uncertainty up to 3.2 kPa (0.46 psid) or 0.92% FS. The estimated uncertainties are for a 95% confidence level.

5.0 CONCLUSIONS AND COMMENTS

The basic methodology used to acquire and reduce blade-mounted pressure transducer data for this report was found to be adequate. The data produced for this report have since been used the calculate the transient forces and momentum on the first stage rotor of this machine and will be presented in a subsequent report(s).

6.0 RECOMMENDATIONS

Based upon the observations of this author and other researchers, the following recommendations are made regarding any future acquisition of blade-mounted pressure transducer data in the CRF:

1. Concerted efforts should be made to assure that the transducers and related wiring are more firmly attached to the blade. Although this set of blade-mounted pressure instrumentation survived longer than any previous set in this machine, further improvement in survival time is necessary. During this test, most of the instrumentation was damaged by the time of 9th data point and two pressure transducers were out from the start. It is suggested that more time be scheduled for the purposes of attaching and verifying the operability of the transducers in subsequent tests.

2. More comprehensive calibration procedures should be employed. Some method of calibrating the transducers in place should be developed.

3. In future tests, much larger data sets need to be created; 25,000 to 30,000 samples is appropriate. Now that the acquisition and reduction process has been defined, larger data sets would not be a problem.

4. Some way of reducing precision error needs to be explored. Replacing the 50 psid range transducers with smaller range transducers is one way to achieve this.

5. A system which determines blade position relative to the distortion screen needs to be developed. Although a good quality 1/rev signal was available off of the rotor; the exact position of the 1/rev pick-up relative to the screen was unknown.

REFERENCES

1. Dr. Albin Bölcs, Adlarf Blade Kulite Measurements , 1993.
2. Mark Burns, Post-processing Function/Analog Tape Digitization System (ATDS), ATDS User's Guide, 28 May 1992 Revision.

APPENDIX A: DATA POINT LIST

Below is a complete list of all the data points obtained using the blade-mounted pressure transducers. In general, blade-mounted strain gage data were obtained at all of the following data points as well. Rows in bold indicate points used in this report.

Table A.1 Blade-Mounted Pressure Transducer Data Points

#	Distortion	RPM*	DV **	Available Transducers
1	3/rev	8400	60	P1,P2,P3,P4,P5,P6,P7,S3,S4,S5,S6,S7
2		8100	60	P2,P3,P4,P5,P6,P7,S3,S4,S5,S6,S7
3		**8100**	**39**	**P2,P3,P4,P5,P6,P7,S3,S4,S5,S6,S7**
4		8400	39	P2,P3,P4,P5,P6,P7,S3,S4,S5,S6,S7
5	8/rev	9100	60	P2,P3,P4,P5,P6,P7,S3,S4,S5,S6,S7
6		10370	60	P2,P3,P4,P5,P6,P7,S3,S4,S5,S6,S7
7		**9100**	**39**	**P2,P4,P5,P6,P7,S3,S4,S5,S6,S7**
8		**10370**	**39**	**P2,P4,P5,P6,P7,S3,S4,S5,S6,S7**
9		13500	60	P2,S3,S4,S5,S7
10		13200	60	P2,S3,S4,S5,S7
11		**13200**	**39**	**P2,S3,S4,S5,S7**
12		13500	39	P2,S3,S4,S5,S7
13	2/rev	14245	60	P2,S3,S4,S5,S7
14		**14245**	**39**	**P2,S3,S4,S5,S7**
15	Clean Inlet	8400	60	P2,P4,P5,S6,S7
16		9100	60	P2,P4,P5,S6,S7
17		8400	38	P2,P4,P5,S6,S7
18		9100	38	P2,P4,P5,S6,S7

* This is the mechanical speed.
** Discharge Value Position
60 = Wide-open (unloaded)
39 or 38 = Peak efficiency (loaded)

APPENDIX B: EXAMPLE DATA FILE

An example of one the computer data files produced during this study is presented below. All of the files were written in a format that can be read into a plotting software package called Tecplot™. This example includes the header and several lines of data:

```
TITLE="ADLARF Blade Mounted Kul. Data; 9100 RPM, 8/Rev"
VARIABLES=T,SS3,SS4,SS5,SS6,SS7,PS2,PS4,PS5,PS6,PS7
ZONE  I=10000
  .0000, -4.7277, -1.9285,  5.4770,   .8771, -9.1653, -3.8892,  2.9949,
1.4219,   .0615, -7.7203,
  .0001, -7.6415, -2.0962,  2.0976,  1.6462, -9.8387, -3.7858,  1.2885,
1.8109,  4.1233,-11.0273,
  .0002, -4.8763, -2.7909, -4.5836,  1.1739, -2.8930,  -.1551,  -.1509,
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  .0003, -1.3826, -3.0904, -9.6721,  -.4993,  4.2896,  3.5274,  -.8358,
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3.6217,  4.9110, 15.3805,
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  .0012, -3.1815, -1.6410,  -.5697,  3.0360, 10.1130, 13.7867, -2.7047,
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-1.7015,   .1354,  9.5482,
  .0014, -4.4749, -5.1387,  3.1722,  7.1650,  6.8709, -2.7522,  6.8719,
2.8560,  4.1110,  9.9931,
      .
      .
      .
```

where;

T = time in seconds
SS# & PS# = static pressure variables; kPa
I = number of sample points